AN ANALYTICAL EXPERIMENTAL STUDY OF POSSIBLE EFFECTS OF GRAVITY ON CRYSTAL WHISKERS

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ABSTRACT

This paper reports on the progress of analytical and experimental efforts to determine if a 1-g environment has any effect on whisker growth. It is found analytically that the best quality whiskers are the ones most likely to be destroyed by gravity. A centrifuge experiment is set up to check this idea experimentally. The centrifuge is also being used to measure directly the effect of increased gravity on crystal growth by vapor deposition where convection is important.

I. INTRODUCTION AND BACKGROUND

The purpose of this investigation is to determine whether or not whisker growth is significantly improved in an earth orbit. This is part of a larger effort to study manufacturing in space. The scope is limited to whiskers to assure a complete and intensive investigation.

Whiskers are high strength, filamentary single crystals. They are of interest mainly because of their high tensile strength which approaches the theoretical limiting strength of a material as shown in Figure 1. Bulk crystal tensile strength is from two to three orders of magnitude below the predicted theoretical value. As the crystals cross section area becomes smaller in the neighborhood of 1 micron^2, the tensile strength increases by about a factor of 100. The smaller the area the greater the tensile strength with the tensile strength being roughly inversely proportional to the diameter.

So far, technology has been unable to fully utilize the high strength potential of whiskers. See Figure 2. This is partly because no rapid mass production method of growing good quality whiskers is available in an earth environment. Whiskers now available are either too short, have multiple branches, or are too scarce to be used in the reinforcement of high strength composites. In a zero-gravity space environment whiskers should grow longer, thinner, and stronger.

Whiskers used to strengthen composits should have a high aspect ratio. The aspect ratio is the ratio of whisker length to the thickness (or diameter). The long thin whiskers have more surface area per unit whisker tension, thus they do not pull free from the plastic matrix when the composite is under tension.

II. WHISKER DESTRUCTION DUE TO GRAVITY

Whiskers may be destroyed by a gravity-field as they grow. In this section we are not interested in the atomic growth process, but in preserving the whisker from mechanical destruction as it grows.

The thinnest whiskers have the highest aspect ratios and tensile strengths. However, the full potential of these small fibers has not been realized because they are not rigid enough to support their own weight so they fall due to gravity to a nearby surface where they adhere. This surface force is quite strong, and using a microscope, the whiskers may be seen sticking to the surface like adhesive tape as it is pealed from the surface. This adhesion stops the growth process. Just how long and thin must a whisker be before it bends under a 1g force and is captured by an even stronger adhesive force.

The gravitational effect on a long thin whisker may be analyzed using the

equation for the deflection of a horizontal cantilever beam as shown in Figure 3.

$$d = \frac{WL^4}{8EJ} \qquad (1)$$

W is the weight per unit length of the whisker, L is the length, E is Young's modules and J is the area movement about the neutral axis. $J = \frac{bh^3}{12}$ for a rectangular cross section of thickness h, and width b.

For tin the following equations:

$$d = 2.3 \times 10^{-8} \frac{L^4}{h^2}$$

or

$$\frac{d}{L} = 2.3 \times 10^{-10} \frac{L^3}{h^2} \qquad (2)$$

result from using $E = 4.5 \times 10^{11}$ dynes/cm^2
$= 7.1$ gr/cm^3
$g = 980 \frac{cm}{sec^2}$

Lets say that if a whisker deflects 20% of its length that it is endangered. Letting d/L = 0.2 in the above equation, we have:

$$L_{max} = 216\, h^{2/3} \qquad (3)$$

L max represents the maximum length that a horizontal tin whisker of thickness h may have without being deflected by more than 20% of its length.

Figure 4 shows L max as a function of h. Whiskers having L and h coordinates falling in region 3 are not affected by gravity. If the L and h coordinates fall in region 1, the aspect ratio is greater than 1000; and the whisker has good bonding properties in a matrix. However, there are no coordinates common to both regions 1 and 3 indicating that all whiskers having desirable aspect ratios are endangered by gravity.

In compression induced whisker growth, experimentors have found that thick whiskers have a terminal length which is much less than the terminal length of thin whiskers. Just how far does this tendency go? We have pointed out that the thinner whiskers are usually destroyed by a gravity-field so we really do not know. Possibly the length would increase several

orders of magnitude as the diameter decreases. That is, 1μ thick whiskers which now are limited to a length of 1 mm may become as long as 100 mm if their thickness is reduced to 0.1μ.

Are there any flaws in this cantilever beam model used here? First the g-field might not be perpendicular to the whisker and the deflection-length ratio of 0.2 is rather arbitrary. However, the whiskers always break off at the base indicating that the base is the weakest point. This suggests that gravity is even more important than predicted by the uniform beam model.

The whisker base is most important in supporting the whisker. In a recent article Gabor and Blocher[1] show a picture of iron whiskers growing using an electron microscope which we show in Figure 5. Note that the base of the whisker is several times thinner than the rest of the whisker. This could easily reduce the rigidity of the whisker by a factor of 100 since the deflection of the cantilever beam in Equation 1 is inversely proportional to h^3.

Has anyone ever seen a whisker fall under the influence of gravity? Hock and Neumann[2] reported in 1954 that whiskers often disappear suddenly presumably having broken off at the root. This may have been due to gravity.

In our lab, whiskers of Ca and Tl have been observed lying flat on the substrate surface, probably due to gravity or vibration since they were sealed under vacuum away from air currents.

Experiments are underway in our lab to systematically increase the effective value of g and note its effect on whiskers of various lengths.

III. THE EFFECT OF ZERO-G ON WHISKERS GROWN BY VAPOR DEPOSITION

Conceivably a gravitational field could affect the atomic whisker growth mechanism. This would be much more likely in the vapor deposition growths which involve the gaseous states. In the vapor deposition process, a source material is slowly vaporized in the hot portion of the furnace and as the vapor moves to the cool region it becomes supersaturated and condenses metal atoms to make a solid which often grows in whisker form. This is done in an inert atmosphere as shown in Figure 6. The diffusion should be very slow; however, in a temperature gradient, convection currents are set up which add to the diffusion in transporting the atoms to the lattice. These circulating currents (due to gravity) are probably

unstable, thus they have an adverse effect on whisker growth. That is, an excess of supercooling could result in massive nucleation which produces polycrystals instead of a single crystal. The convection is due to warm and cool gas having a different density in the presence of a gravitational field. So at zero-gravity, convection is removed and diffusion will produce a more uniform vapor for better crystal growth.

An experiment is underway to test indirectly the above hypothesis. If 1-g produces an adverse effect on whisker growth, then 2-g should produce an even more adverse effect, etc. By applying several g's of acceleration to the whiskers during the growth by vapor deposition and by comparing this growth to 1-g growth, one would then predict the effects of 0-g.

Vapor deposition growth is suited to materials having a high vapor pressure at their melting point. Cadmium with a m.p. = 321°C and a vapor pressure .1 mm (at m.p.) could be used.

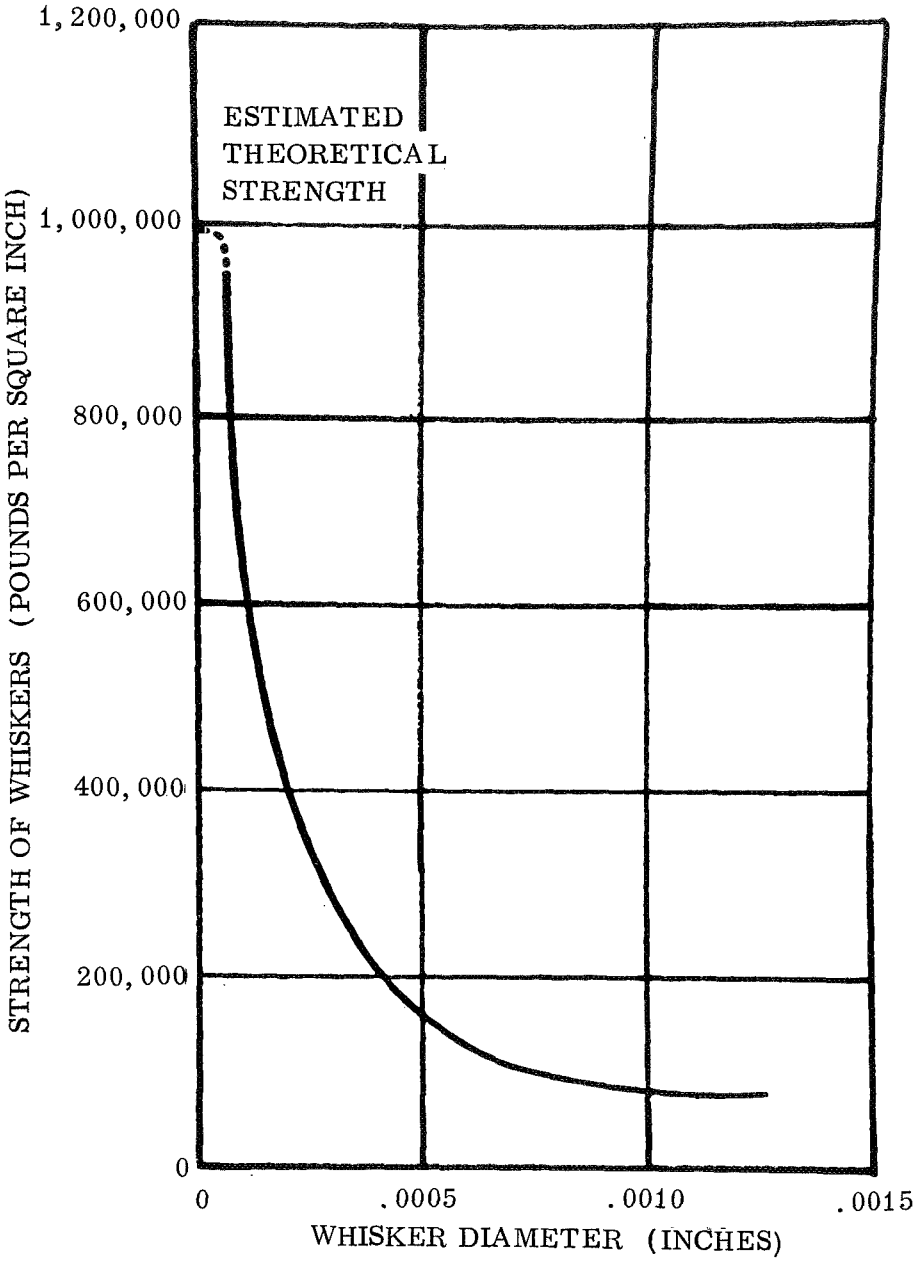
A source material cadmium is placed in the warmest portion of a furnace as shown in Figure 6. The Cd. slowly vaporizes and condenses in the cooler regions of the furnace. If the temperature gradient along the furnace is carefully controlled, the vapor will condense in the form of single crystal whiskers.

The experimental arrangement is shown in Figure 7. The gradient furnace is placed on a 1 m arm in the 0-75 G centrifuge. The centrifuge is equipped with an optics system, slip rings and gas lines, to monitor and control the furnace during crystal growth. A growth requires about 12 hours.

REFERENCES

1. Thomas Gabor and John M. Blocher, Jr., Journal of Applied Physics vol. 40, No. 7, p. 2696, 1969.

2. F. Hock and K. Neumann, Zeits f. Phy. Chem., 2, p. 241 (1954).



Whisker strength is a function of whisker diameter and drops sharply within the first .0005 inch, slowly decreasing with further increases in diameter. The curve shown represents the relationship of strength to diameter in one type of iron whisker. From S. S. Brenner. Scientific American, Vol. 203, No. 7, p. 65.

FIGURE 1

Reason for Whisker Study

1. Whiskers are the strongest materials known to man

2. Whiskers are the most nearly perfect crystals

Present Problems With Whiskers

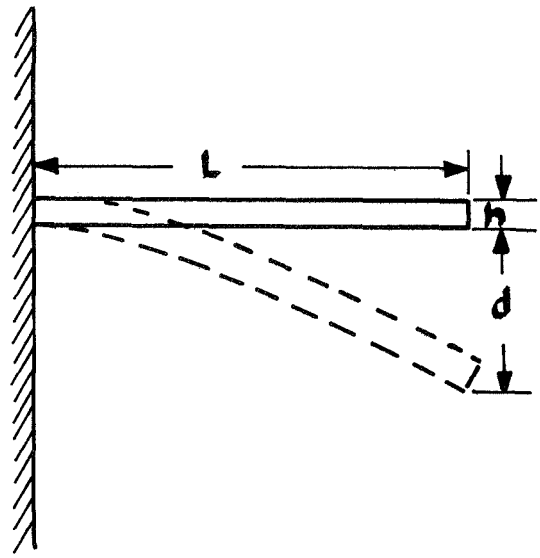
1. Too Short

2. Growth too slow

3. Technology has thus far been unable to build strong structures from whisker fibers.

FIGURE 2

CANTILEVER WHISKER
BEAM BENDING DUE TO GRAVITY



$$d = \frac{wL^4}{8EJ} \qquad J = \frac{bh^3}{12}$$

Where

W = Weight per unit length

L = Length

h = Vertical thickness

E = Youngs Modulus = 4.5×10^{11} dynes/cm^2

J = Area Moment about neutral axis

b = Whisker thickness

$$.2 = \frac{d}{L} = \frac{wL^2}{8EJ} = 2.3 \times 10^{-10} \frac{L^3}{h^2}$$

$$L_{MAX} = 216\, h^{2/3}$$

Good Aspect Ratio is L/h = 1000

FIGURE 3

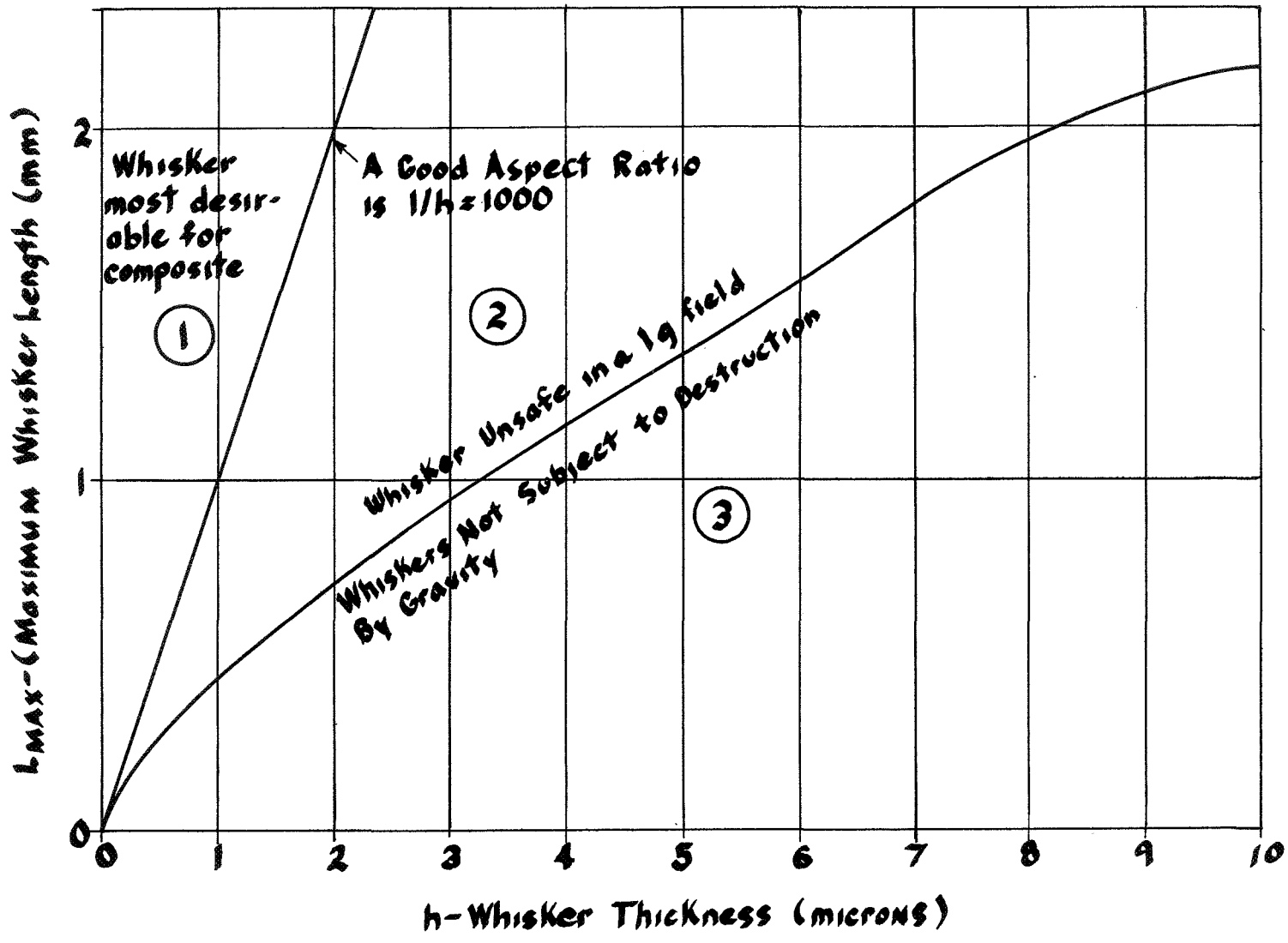
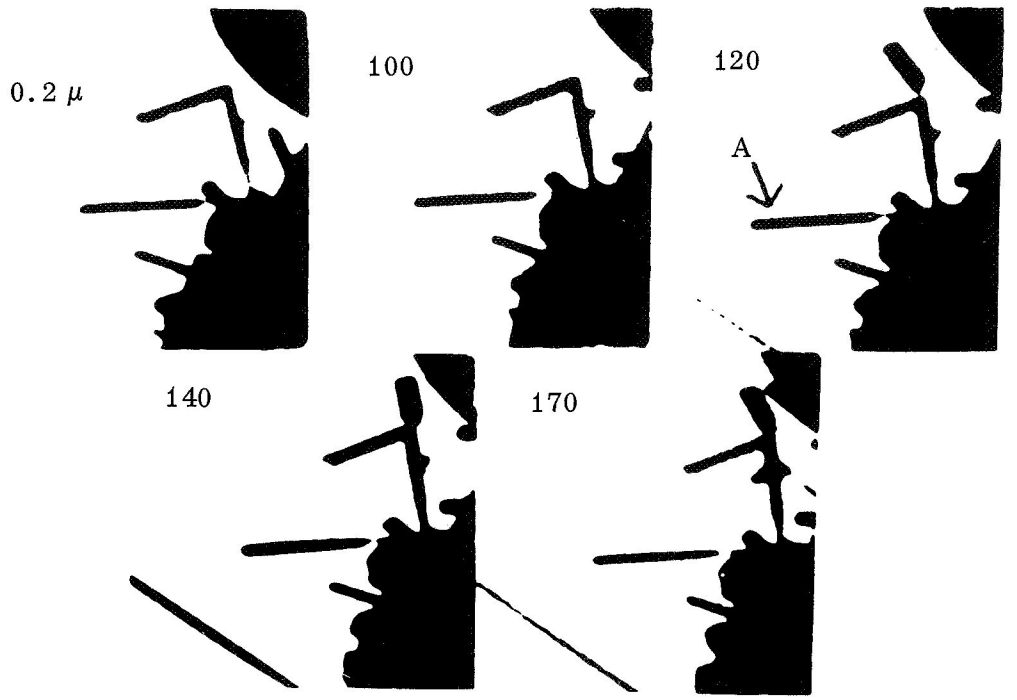

Whisker most desirable for composite
A Good Aspect Ratio is l/h=1000
1
2
Whisker Unsafe in a 1g field
Whiskers Not Subject to Destruction By Gravity
3
0
1
2
3
4
5
6
7
8
9
10
L_{MAX}-(Maximum Whisker Length (mm)
h-Whisker Thickness (microns)

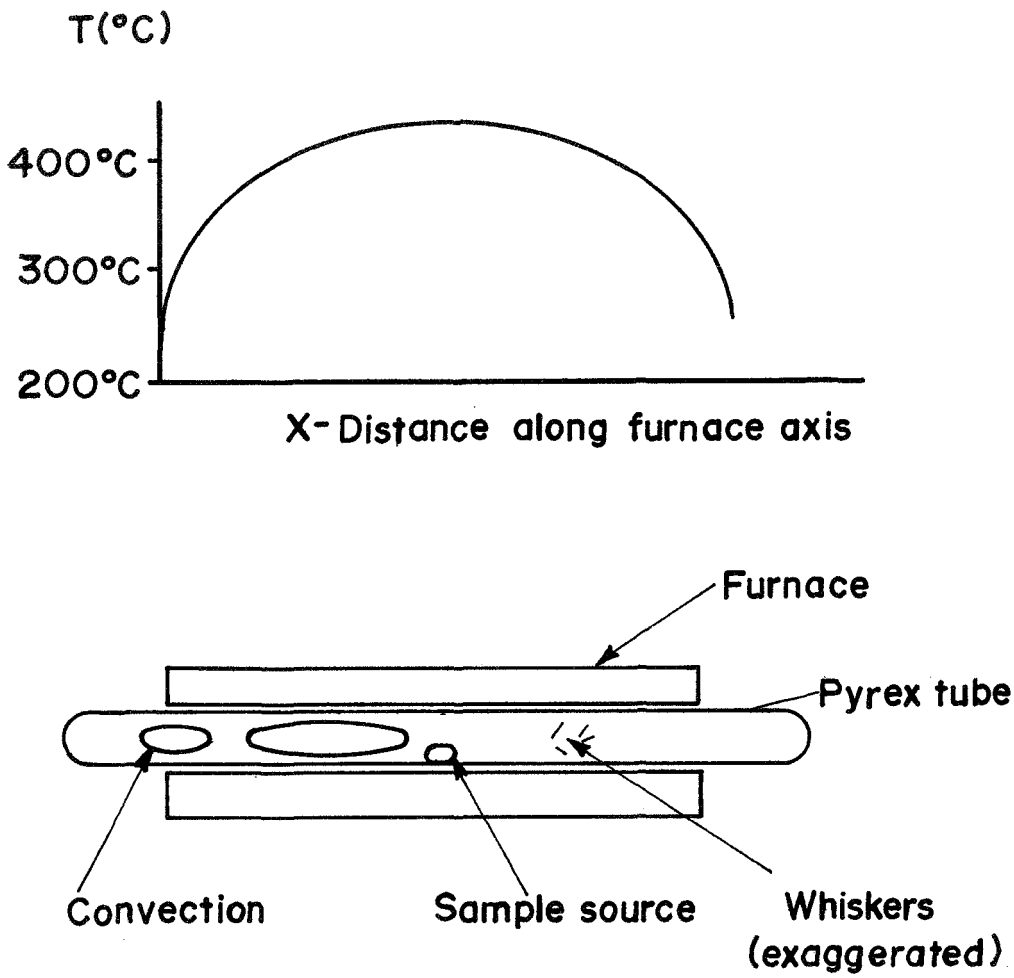
FIGURE 4



IRON WHISKERS

From Gabor and Biocher. J. Appl. Phy., Vol. 40, No. 7, 1969, p. 2703.

FIGURE 5



THE VAPOR DEPOSITION METHOD OF WHISKER GROWTH.

FIGURE 6

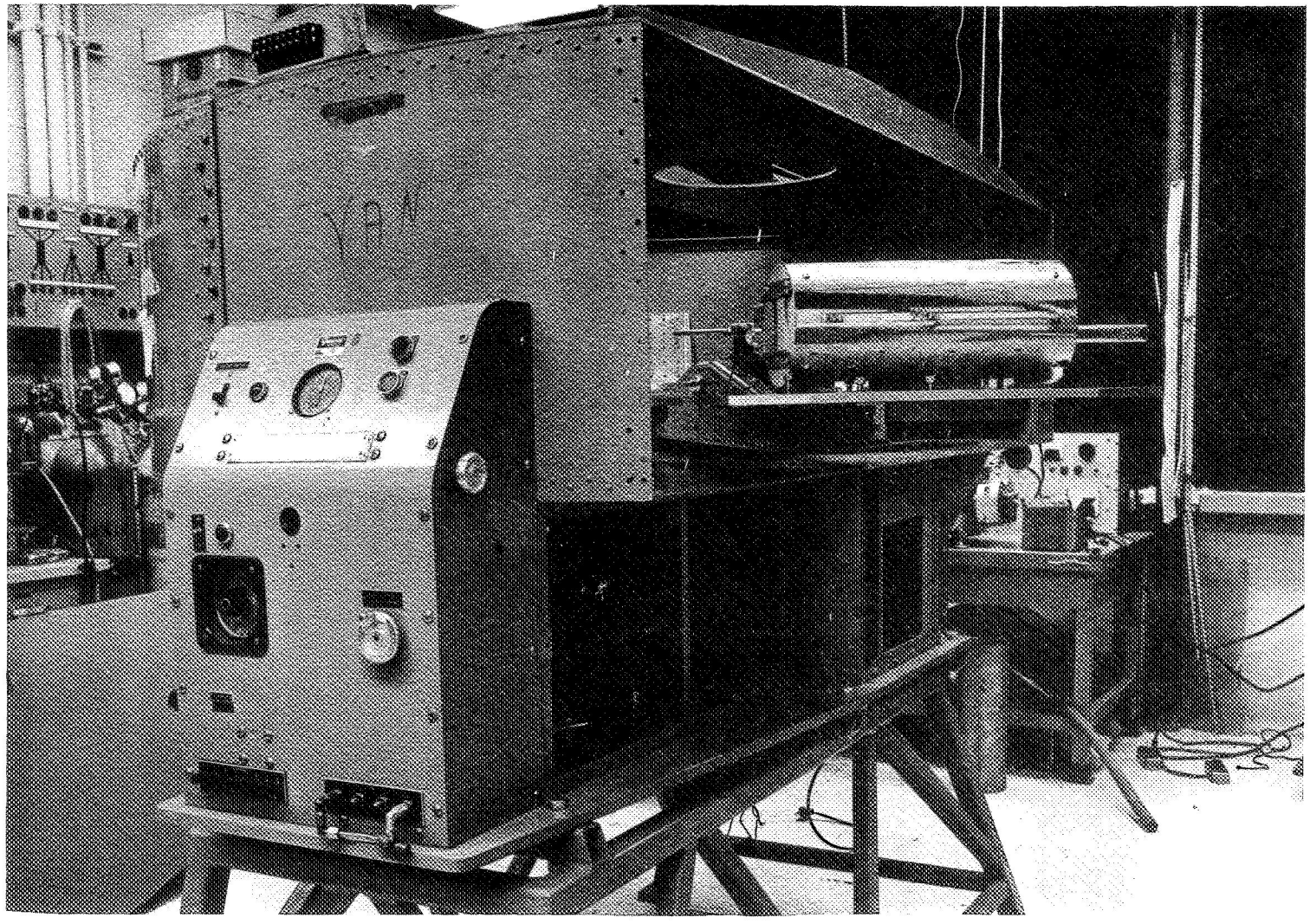


FIGURE 7